Lunar Background

During the last decade research has been conducted on the lunar South Pole. However, what makes such a location viable and so important? The most important aspect to consider is that the lunar South Pole favors thermal and solar energy conditions primarily because it is near constant sunlight. Thus such a location is critical for a continuous operation of a solar power system.

The rim of Shackleton crater is a potential high-illumination site and has been determined using radar DEM to have the most illumination at the South Pole. However since Shackleton has been shaded from the sun for a prolonged time, it is believed to have served as a "cold trap", thus preserving volatiles.

Because of its strategic location to both permanent light and permanent darkness, this location can provide a future colony with both energy and preserved resources. Since the rim of Shackleton crater is exposed to light for more than eighty percent of the time, it is considered location for the deployment of solar array. The figure below contains Lunar Reconnaissance Orbiter (LRO) data that reinforces this point (yellow spots are spots of near-constant sunlight). Likewise, Shackleton crater is in constant view of the earth and so minimizing loss of communication.

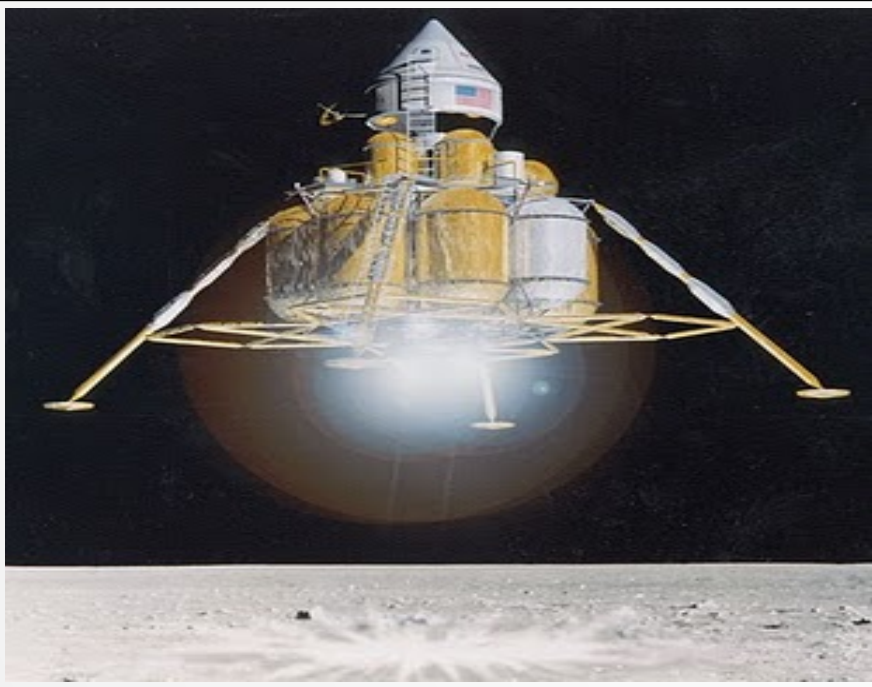Maximum illumination sites (South Pole)

Optimization Model for a Future Lunar Colony

Abstract:

The objective of this project is to develop an optimization model for lunar colonization that would account for current technology as well as emerging technology. The model uses the returns from the mission to compute an efficiency of the colony as well as other useful statistics to compare the different configurations. To aid in the evaluation of the financial, scientific, and future mission infrastructure returns the lunar colony's objectives were broken down into six parts. Once completed, the missions were compared on the revenue, cost, scientific return, and future mission savings to calculate a mission cost-time ratio and mission efficiency.

Optimization

To optimize the colony, multiple configurations for the colony were compared to each other as well as to the Constellation program. Constellation was chosen because of it's prior NASA focus and objective to help NASA create a more permanent lunar presence. Each configuration was evaluated based on its financial and scientific return as well as the future mission savings. The configurations varied by crew expansion rate, flight vehicle ratios (lift:transit:landing), and number of units of each component sent to the lunar surface. This in turn varied the missions financial return, scientific return, and future mission savings. Overall, twenty configurations were compared as well as the Constellation program. The primary evaluations were carried out using the following formulas:

$$\eta_M = \frac{\tan^{-1}\left(e^{\left(\frac{k_s * C_M}{5 * |C_M|}\right)}\frac{R_{CTA}}{R_{CTI}}\right)}{\pi} + \frac{1}{2}$$

Where:

R_{CTA} = Actual Mission Cost Time Ratio (C_M/T_M)

R_{CTI} = Ideal Mission Cost Time Ratio ($E_M/T_D * 24$)

η_M = Mission Efficiency

k_s = Scientific Return

C_M = Mission Cost

Using these parameters, the final optimized design was a system that utilized a 2-year crew expansion rate, 1 of each flight vehicle in a 1:1:1 flight vehicle ratio, and 1 robotic vehicle..

Colony Parameters

- **Location**: Rim of Shackleton Crater
- **Initial Size**: 4 personnel
- **Maximum Size**: 28 personnel
- **Electrical Power**: Solar photovoltaic Arrays with battery back-up
- **Earth-Moon Transport**: Reusable Light Earth-LEO Lift Vehicle, Expendable Heavy Earth-LEO Lift Vehicle, Reusable LEO-LLO Transit Vehicle, Reusable LLO-Moon Lander

Lunar Objectives

Geology:

Obtaining lunar history, topology as well as mapping of minerals, rare elements, and water.

Astronomy:

Radio, optical and ultra-violet mapping of the universe beyond the Moon. Less interference on the Moon means clearer mapping.

Agriculture:

Implementation of agriculture towards a self-sustaining colony. Excess crops would be used for future missions beyond the Moon.
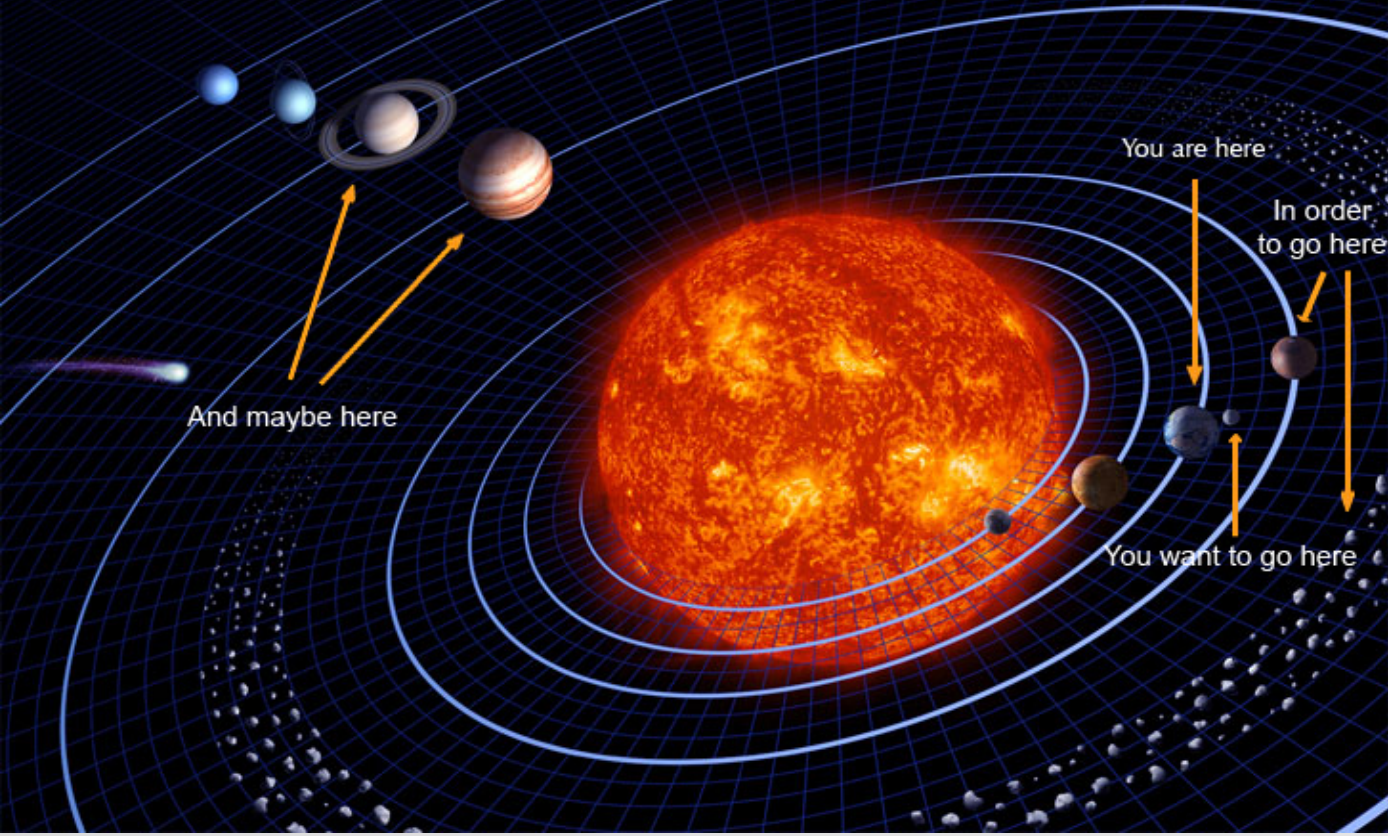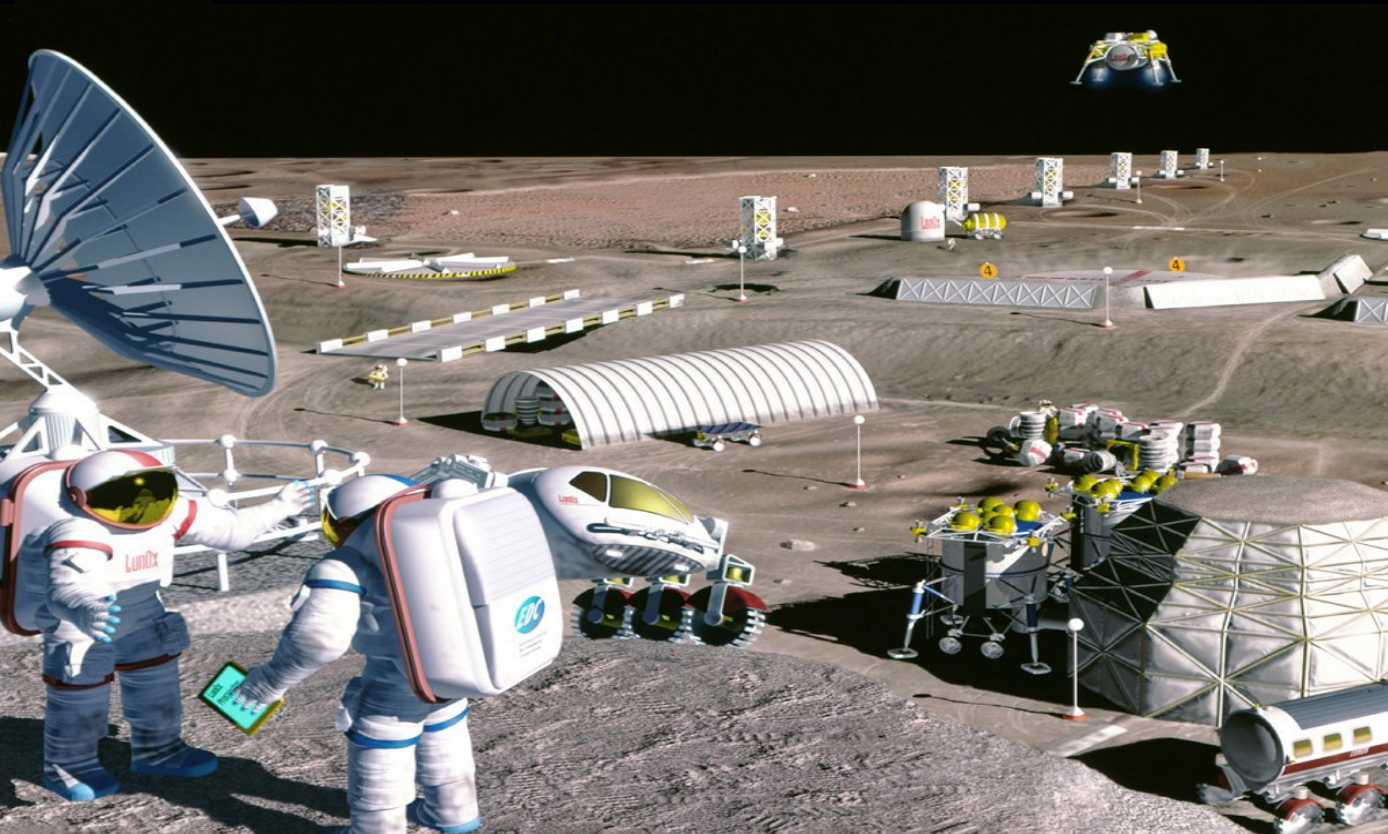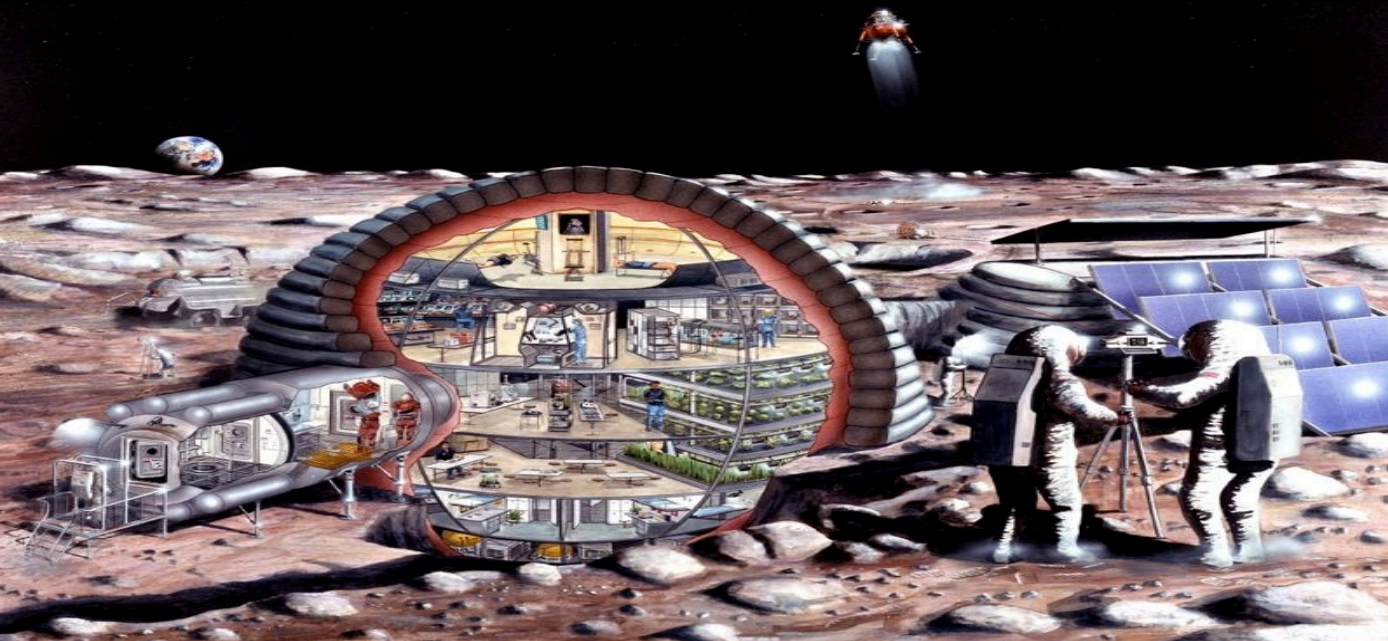
Mining:

Using the data from the geological research of the Moon to extract rare elements, water and minerals. This includes Helium-3, an element useful in the development of nuclear fusion technology.

Exploration:

Developing techniques and infrastructure on the moon to help aid future missions beyond the Moon. This includes the storage of extra food and oxygen, refinement of exploration procedure, and the training of astronauts bound for other destinations.
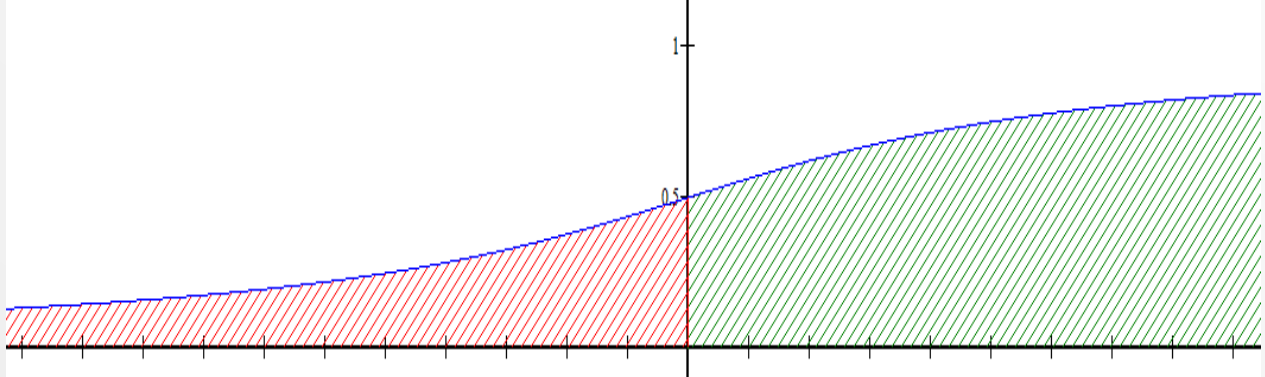
Research:

To focus on the effect of the long duration space flight on the crew as well as to provide opportunity for private research to be conducted on the moon.

Optimization Basic Model

Basic $y=\arctan(x)/\pi+1/2$ curve where the model gets its rough shape and behavior. The red area contains missions that are between 0% and 50% efficient; the green area contains missions between 50% and 100% efficient. The range of the function is 0 to 1 (0% to 100%) exclusive, and is defined for all real values of x.

Optimization Analysis

Mission Profile	Mission Expenditures	Mission Revenue	Scientific Return Coefficient	Future Mission Savings	Total Mission Cost	Usable Mission Time (hours)	Mission Cost-Time Ratio	Crew Member Cost-Time Ratio	Mission Efficiency
NC0+C0	$7,746,475,431.42	$28,219,169.60	3	$4,962,880,786.22	$2,755,375,675.60	1,635,020	$1,685.04	$60.18	27.06%
NC0+C1	$7,746,475,431.42	$1,670,719,169.60	3	$4,962,880,786.22	$1,112,875,675.60	2,452,800	$453.72	$16.20	42.61%
NC0+C2	$7,746,475,431.42	$520,969,169.60	3	$5,008,702,311.25	$2,216,804,150.57	1,430,800	$1,549.35	$55.33	28.37%
NC0+C3	$7,746,475,431.42	$549,188,339.20	3	$4,962,880,786.22	$2,234,406,506.00	1,430,800	$1,561.65	$55.77	28.25%
NC1+C0	$8,598,209,918.31	$42,328,754.40	4	$5,062,210,066.98	$3,493,671,096.93	1,635,200	$2,136.54	$76.31	28.11%
NC1+C1	$8,598,209,918.31	$1,684,828,754.40	4	$5,062,210,066.98	$1,851,171,096.93	2,452,800	$754.72	$26.95	41.01%
NC1+C2	$8,598,209,918.31	$508,031,592.02	4	$5,108,031,592.02	$2,955,099,571.89	1,430,800	$2,065.35	$73.76	28.64%
NC1+C3	$8,598,209,918.31	$549,188,339.20	4	$5,062,210,066.98	$2,986,811,512.13	1,430,800	$2,087.51	$74.55	28.47%
NC2+C0	$8,791,852,523.06	$28,219,169.60	4	$5,062,210,066.98	$3,701,423,286.48	1,635,200	$2,263.59	$80.84	27.55%
NC2+C1	$8,791,852,523.06	$1,695,410,943.00	4	$5,062,210,066.98	$2,034,231,513.08	2,452,800	$829.35	$29.62	40.38%
NC2+C2	$8,791,852,523.06	$528,023,982.00	4	$5,108,031,592.02	$3,155,796,969.04	1,430,800	$2,205.62	$78.77	27.96%
NC2+C3	$8,791,852,523.06	$549,188,339.20	4	$5,062,210,066.98	$3,180,454,116.88	1,430,800	$2,222.85	$79.39	27.84%
NC3+C0	$9,074,166,826.90	$42,328,754.40	5	$5,186,371,667.94	$3,845,466,404.56	1,635,200	$2,351.68	$83.99	30.53%
NC3+C1	$9,074,166,826.90	$1,705,993,131.60	5	$5,186,371,667.94	$2,181,802,027.36	2,452,800	$889.51	$31.77	41.74%
NC3+C2	$9,074,166,826.90	$535,078,754.40	5	$5,232,193,192.98	$3,306,894,879.52	1,430,800	$2,311.22	$82.54	30.79%
NC3+C3	$9,074,166,826.90	$549,188,339.20	5	$5,186,371,667.94	$3,338,606,819.76	1,430,800	$2,333.38	$83.34	30.64%
NC4+C0	$9,267,809,431.65	$28,219,169.60	5	$5,186,371,667.94	$4,053,218,594.11	1,635,200	$2,478.73	$88.53	30.05%
NC4+C1	$9,267,809,431.65	$1,716,575,320.20	5	$5,186,371,667.94	$2,364,862,443.51	2,452,800	$964.15	$34.43	41.26%
NC4+C2	$9,267,809,431.65	$535,078,754.40	5	$5,232,193,192.98	$3,500,537,484.27	1,430,800	$2,446.56	$87.38	30.29%
NC4+C3	$9,267,809,431.65	$549,188,339.20	5	$5,186,371,667.94	$3,532,249,424.51	1,430,800	$2,468.72	$88.17	30.11%
Baseline-Constellation	$97,000,000,000.00	$0.00	4	$1,417,896,000.00	$95,582,104,000.00	343,200	$278,502.63	$69,625.66	3.34%

Sustainability

Habitat Atmosphere
Methods for maintaining oxygen levels
Initial method: Carbon Scrubbers
Leaning towards → Self-Sustaining colony: Agriculture

Lunar Agriculture

System	Cost of System (4 people)	Expanded to 28
Aeroponics	$12,183.99	$18,183.99
Hydroponics	$8,750.99	$17,750.99
Geoponics	$800.00	$5,600.00
Shipping from Earth	$2,341,308.56	$11,706,542.82

System	Tomato growth rate (days)	Annual Yield (kg)	Potato Growth Rate (days)	Annual Yield (kg)	Wheat Growth Rate (days)	Annual Yield (kg)	Herb Growth Rate (days)	Annual Yield (kg)
Aeroponics	31	1121.73	40	196.74	30	52.8	28	35.59
Hydroponics	36	965.93	52	151.33	35	45.26	33	30.2
Geoponics	57	610.06	70	112.42	60	26.4	42	23.73
Shipping from Earth	57	304.81	90	87.44	120	13.2	42	23.73

System	1st year cost	30 year cost	$/kg
Aeroponics	$2,475,332.45	$2,475,332.45	$58.65
Hydroponics	$4,770,127.03	$4,770,127.03	$133.31
Geoponics	$4,690,617.13	$4,690,617.13	$202.37
Shipping from Earth	$28,095,702.77	$842,871,083.04	$65,463.68

Water & Waste Management
MELiSSA
Micro Ecological Life Support System Alternative
Water treatment with Microbes
CEBAS
Closed Equilibrated Biological Aquatic System
Fish farm oriented (maintaining aquatic life using algae)
Black-water treatment (human waste)

Habitat Considerations

Criteria	Weighting	Mobile	Mobile (Weighted)	Sulfur-Concrete	Sulfur-Concrete (Weighted)	Rigid Frame	Rigid Frame (Weighted)	Inflatable	Inflatable (Weighted)
R&D Cost	6%	4	2%	6	4%	8	5%	7	4%
Unit Cost	23%	3	7%	10	23%	1	2%	5	12%
Functionality	12%	6	7%	3	4%	6	7%	8	6%
Power supply	12%	3	4%	10	12%	10	12%	10	12%
Multi-Environment Usage	12%	9	11%	2	2%	9	11%	9	11%
Ease of Assembly	14%	10	14%	4	6%	5	7%	9	13%
Vulnerability	21%	7	15%	6	13%	10	21%	8	17%
Totals	100%	42	60%	41	63%	49	65%	56	74%
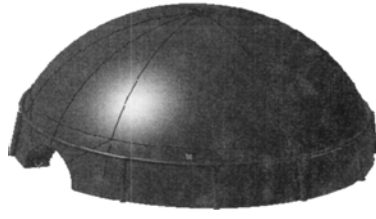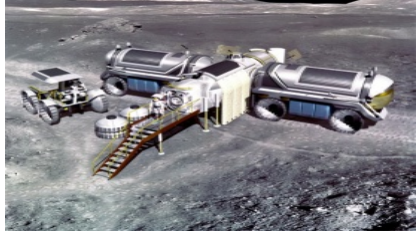
Inflatable Habitat Advantages

The inflatable habitat design had a few significant advantages over its competitors. It can be designed for multiple environments, so that it could be useful on Mars or the surface of an asteroid as well as the Moon. It's compact, which allows it to be transported easily. Since the assumed habitat structure was assumed to have modular interior components and exterior sockets, deployment is as easy as inflating the habitat and placing the components inside and out. The fixed location allows for near-constant solar power for the base and constant communication with the Earth. Radiation and micrometeorite protection is also straight-forward. By using the regolith to make a shield over the habitat radiation and micrometeorites are stopped before they get to the astronauts.

Mission Profile Definitions:

NC0: One unit of each component is used, flight vehicle ratio 1:1:1

NC1: 5 units of non-system components (robots, oxygen storage, flight vehicles) and 1 unit for system components used, flight vehicle ratio 1:1:1

NC2: 5 units of non-system components and 1 unit of system components used, flight vehicle ratio 1:2:1

NC3: 10 Units of oxygen storage and robots, 5 units of each flight vehicle, and 1 unit each of system components used, flight vehicle ratio 1:1:1

NC4: 10 Units of oxygen storage and robots, 5 units of each flight vehicle, and 1 for system components used, flight vehicle ratio 1:2:1

C0: Add 4 crew members every 5 years for 30 years. Private Research is possible in this architecture after 30 years.

C1: Add 4 crew members every 2 years, then continue working for 30 years. Private Research is possible in this architecture after 12 years.

C2: Add 4 crew members every 4 years, then continue working for 30 years focusing on Agriculture. Private Research is possible after 24 years in this architecture.

C3: Add 4 crew members every 4 years, then continue working for 30 years focusing on Mining. Private Research possible after 24 years in this architecture.